Sand-Cement Concrete in the Century-Old Camarasa Dam

A. Blanco, Ph.D.[1]; I. Segura, Ph.D.[2]; S. H. P. Cavalaro, Ph.D.[3]; S. Chinchón-Payá, Ph.D.[4]; and A. Aguado, Ph.D.[5]

Abstract: Sand-cement emerged in the early twentieth century as an alternative binder in infrastructures that required a significant amount of concrete volume in order to reduce the costs associated with portland cement. This binder was first used in the United States in several dams before being applied in Camarasa Dam in Spain. Nearly a century after its construction, the dam exhibits degradation phenomena in the downstream face, manifested by losses of mass. The present study aims at assessing the state of the sand-cement concrete in Camarasa Dam and evaluate whether the degradation observed could affect the safety and functionality of the 95-year-old dam. For that, the state of the art on sand-cement is reviewed and an experimental program of physical, mechanical, and chemical tests is performed on samples from the dam. The results reveal that the degradation phenomena may be attributed to physical causes and a general degradation of the concrete properties is discarded as well as any effect on the safety and functionality of the dam. **DOI: 10.1061/(ASCE)CF.1943-5509.0000823.**

Author keywords: Sand-cement; Concrete dam; Freeze-thaw cycle; Leaching.

Introduction

Sand-cement is a binder obtained by blending portland cement and silica sand, patented in 1893 in Denmark by L.T. Smidth Company (Solana 1916). At that time, the main interest of using sand-cement was the cost savings derived from the acquisition and transportation of the cement. Nevertheless, from a current perspective this type of binder also contributed to a more sustainable construction due to the reduction in clinker consumption. Even though the consumption of sand-cement declined at the beginning of the twentieth century due to the significant cost reduction of cement, shortly after it became popular again in the United States because of the government policies promoting the construction of hydraulic works, such as concrete dams (Pisani 2002).

Sand-cement was particularly advantageous for this type of application given the remote location of the work sites (far from cement plants and railways) and the significant amount of binder required. Prior to the construction of these hydraulic works, the U.S. Reclamation Service conducted an extensive research to evaluate the properties of this material (Coghlan 1913). The results revealed the importance of the sand selection in order to ensure a good performance of the sand-cement. After the study, several concrete dams were built in the United States employing sand-cement: Arrowrock Dam in Idaho (1915), Lahontan Dam in Nevada (1915), and Elephant Butte Dam in New Mexico (1916).

The technology of the sand-cement was subsequently exported to Spain and first applied in the construction of Camarasa Dam (1920), which was the highest dam in Europe at the time at 102 m in height (Díez-Cascón Sagrado and Bueno Hernandez 2001). With the Spanish Civil War (1936–1939) and World War II (1939–1945), the scarcity of construction materials favored even more the application of sand-cement, which was used in the construction of Jandula Dam (1932), Rumblar Dam (1941), and Tranco de Beas Dam (1945). The decline of sand-cement use in Spain arrived with the development of the cement industry.

The fact that some of these concrete dams are now approximately 100 years old raises the question of the long-term performance of this material and how it may affect the safety and functionality of the dams, given the lack of studies in the literature on this issue. In the case of Camarasa Dam, reports requested over the years by the managing organization of the dam suggest a loss of specific weight in the body of the dam. Furthermore, a degradation phenomenon in the downstream face manifested by the loss of mass was also detected. This highlights the need to conduct further research on these sand-cement concretes and assess whether deterioration processes of the material could affect the global structure.

Therefore, the objective of the present paper is to evaluate the performance of the 95-year-old sand-cement concrete used in the construction of Camarasa Dam. To this end, an experimental program was conducted involving physical and mechanical tests as well as techniques to identify possible chemical reactions leading to the degradation of the concrete.

[1]Dept. of Construction Engineering, Universitat Politècnica de Catalunya, Jordi Girona 1-3, C1202, 08034 Barcelona, Spain (corresponding author). E-mail: ana.blanco@upc.edu

[2]Smart Engineering S.L., Jordi Girona 1-3, Parc UPC K2M-202c, 08034 Barcelona, Spain; formerly, Dept. of Construction Engineering, Universitat Politècnica de Catalunya, Jordi Girona 1-3, C1202, 08034 Barcelona, Spain. E-mail: ignacio.segura@smartengineeringbcn.com; ignacio.segura@upc.edu

[3]Lecturer, Dept. of Construction Engineering, Universitat Politècnica de Catalunya, Jordi Girona 1-3, B1-106, 08034 Barcelona, Spain. E-mail: sergio.pialarissi@upc.edu

[4]Dept. of Architectonic Constructions, Universidad de Alicante, Carretera de San Vicente del Raspeig s/n, 03690, San Vicente del Raspeig, Alicante, Spain. E-mail: s.chinchonpaya@ua.es

[5]Professor, Dept. of Construction Engineering, Universitat Politècnica de Catalunya, Jordi Girona 1-3, C1-202, 08034 Barcelona, Spain. E-mail: antonio.aguado@upc.edu

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Background on Sand-Cement

Selection of the Type of Aggregate

The U.S. Reclamation Service was the first organization to conduct extensive scientific research to evaluate the properties of sand-cement prior to the construction of the Arrowrock and Elephant Butte Dams (Coghlan 1913). One of the main aspects of the study was the sand selection based on its chemical composition.

In a completely hydrated cement paste, the calcium silicate hydrate phase (C-S-H) represents between 50 and 60% of the volume of solids, thus determining the properties of the paste. In sand-cement concrete mixes, the amount of C-S-H is smaller in comparison with portland cement mixes due to the smaller amount of clinker in the former. In this regard, the use of sands containing a certain compound that can react with the phases of the hydrated cement paste to form C-S-H would be of great interest to ensure a quality sand-cement. Some rocks, particularly those of igneous origin, contain a certain amount of silica in the form of soluble silica or colloidal silica that is very reactive. Therefore, if sand containing colloidal silica is mixed with portland cement, this silica will react with the calcium hydroxide phase (portlandite) of the hydrated cement paste to produce C-S-H.

Table 1, previously published in Coghlan (1913), shows a wide range of material that was tested by the U.S. Reclamation Service and that proved to produce a satisfactory mix with portland cement. The samples were obtained from locations near the sites where the dams were constructed and some other locations in the United States. The notation for such locations is Elephant Butte (EB), Boise in Idaho (B), Lahontan in Nevada (L), and Los Angeles (LA). The quartz employed in sample R10 corresponds to a material that 90% of the particles are smaller than 0.074 mm in size (sieve no. 200).

The colloidal silica in the materials of Table 1 makes them suitable for the manufacturing of sand-cement. Most of the silica in each material, once mixed, is activated by the grinding of the portland cement and the sand. Furthermore, the presence of silica in the mix before the grinding enables reaching a higher degree of fineness, which leads to a high impermeability (Billings 1920).

Mechanical Properties

The research conducted by the U.S. Reclamation Service also covered the study of the consistency, the setting time, as well as the compressive and tensile strengths of different mixes of sand-cement. For that, portland cement was blended with sands of different nature such as sandstone, basalt, and tufa (Coghlan 1913).

The sand-cement mixes were produced in the laboratory, reproducing the practices and manufacturing conditions employed on site. The cement and the sand were blended to ensure that 90% of the particles are smaller than 0.074 mm (sieve no. 200). The possibility of achieving superior fineness was discarded in the study. Standard proportions 1:3 (cement to sand proportion) were used in the mixes as well as standard sand. The consistency tests showed that the workability of fresh sand-cement mixes were very close to that of portland cement with the exception of the mixes containing tufa. The setting time experienced no significant variation when using sand-cement mixes with regard to portland cement mixes.

The compression tests were conducted on 5.08 cm (2 in.) cubic mortar specimens and the results obtained are shown in Table 2. Taking into account that the sand-cement mixes contain less amounts of clinker than that of portland cement, an equal or lower compressive strength of the former was expected. The results reveal that the compressive strengths of sand-cement are in line with the typical strengths at the time for portland cement.

The results of the tension tests that correspond to the previous series are presented in Table 3. Note that the portland cement employed in all sand-cement mixes was the same. The values indicate that the tensile strength of sand-cement ranges between 10 and 20% of the compressive strength, which is in the order of magnitude of portland cement mixes.

The results obtained indicated that the sand-cement was a competitive material to be used as binder both from the technical and economic point of view, as long as the type of sand is adequately selected and the mix is blended up to the required fineness. Currently, it is known that the fineness of the cement increases the cement hydration rate and, consequently, result in a higher value of initial hydration heat (Kumar Mehta and Monteiro 2006). The effects of fineness on cement pastes are lower porosity and correspondingly higher strength, which occur during the first 7 days. Subsequently, the differences tend to disappear when the mixes reach the same degree of hydration.

Studies performed by A.W.K. Billings in the decades of 1920 and 1930 allowed establishing equivalence in terms of strength between conventional concrete and sand-cement concrete. According to those studies, adding 275 kg of sand-cement to the mix (with a clinker content ranging from 50 to 55% by weight) is equivalent to adding between 230 and 250 kg of cement. In other words, to obtain a similar response of the material, the sand-cement concrete requires between 137 and 151 kg/m^3 of cement, whereas a conventional concrete requires 230–250 kg/m^3. This represents cement savings of 100 kg/m^3 (Martínez i Roig 1995).

Table 1. Chemical Analysis of Rocks Suitable for the Grinding with Portland Cement (Reprinted from Coghlan 1913)

	Sample number, rock type, and location									
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
	Basalt	Basalt	Granite	Granite	Tufa	Tufa	Basaltic tufa	Sandstone	Sandstone	Quartz
Chemical composition	EB	EB	B	B	EB	LA	L	EB	EB	—
SiO_2	44.72	48.08	74.88	74.64	75.66	72.32	50.96	80.52	82.40	99.60
Fe_2O_3	14.30	16.06	1.14	1.14	2.12	2.01	6.57	2.00	1.40	0.31
Al_2O_3	19.26	15.39	13.60	13.42	11.76	13.85	18.37	10.02	10.00	—
CaO	8.30	7.78	0.90	0.80	2.30	1.20	10.20	0.80	0.80	—
MgO	7.48	6.64	0.37	0.39	1.78	0.39	0.45	0.71	0.61	—
K_2O	2.30	1.60	3.89	3.86	—	N.D	3.92	3.85	1.31	—
Na_2O	2.00	3.20	3.35	3.38	—	N.D	—	—	0.86	—
SO_3	—	—	—	—	—	0.31	—	—	—	—
H_2OCO_2	1.64	1.89	0.88	1.66	5.42	3.78	7.26	2.10	1.90	—
Colloidal silica	12.57	19.00	2.41	2.37	14.60	4.01	12.98	7.18	6.42	1.64

Table 2. Compressive Strength of Sand-Cement (Reprinted from Coghlan 1913)

Mix characteristics		Compressive strength (MPa)			
Component	Content (%)	7 days	28 days	3 months	6 months
Sandstone	50	15.23	24.16	26.36	28.56
Sandstone	50	10.55	23.28	17.58	28.12
Sandstone	50	7.03	16.27	19.33	24.61
Sandstone	60	5.62	9.77	10.12	13.18

Table 3. Tensile Strength of Sand-Cement (Data from Coghlan 1913)

Mix characteristics		Tensile strength (MPa)				
Component	Content (%)	7 days	28 days	3 months	6 months	1 year
Basalt	35	1.62	2.57	2.71	3.38	3.45
Basalt	40	1.27	2.32	2.78	2.99	3.23
Basalt	45	1.37	2.21	2.78	3.13	3.34
Basalt	50	1.30	2.11	2.71	2.99	2.92
Basalt	55	1.06	1.97	2.39	2.67	2.71
Basalt	60	0.91	1.51	2.60	2.74	2.81
Basalt	70	0.67	1.69	2.00	2.32	2.46
Basalt	80	0.42	1.16	1.37	1.65	2.33
Tufa	50	1.58	2.67	3.62	3.73	4.11
Tufa	60	0.98	1.79	3.23	3.67	3.76
Tufa	70	1.06	1.62	2.85	2.95	3.18
Sandstone	40	1.58	2.67	2.85	2.95	3.13
Sandstone	50	1.69	2.18	2.53	2.67	2.71
Sandstone	60	0.88	1.72	2.04	2.39	2.46
Portland cement	0	1.72	3.23	3.52	2.78	2.11
Portland cement	0	1.65	2.50	2.71	2.71	2.74

Manufacturing and Cast-In Place

The manufacturing of sand-cement started with the performance of tests of the sand selected for the mix, which revealed whether the material was altered from its natural content and the silica content in it. If the material did not contain colloidal silica, its use was discarded. The mix proportions of the sand-cement were defined depending on the strength requirements, reducing the content of portland cement as the amount of colloidal silica in the sand increased. The rock was pulverized before being mixed with portland cement. This procedure refined the material so that 100% passed the sieve no. 200. According to Coghlan (1913), a finer material than that previously mentioned does not mix correctly with portland cement.

Regarding the location of the manufacturing facilities, the binders employed in the concrete usually came from nearby factories, which ensured a quality control of the raw materials, the manufacturing process, and the final product. However, when the volume of concrete was significant cement factories were constructed in the same worksite of the dam. Furthermore, given the amount of cement in the concrete at the time, ranging from 200 to 250 kg/m^3, and the possibility of placing higher volumes of concrete in situ, required the installation of refrigeration systems for concrete in order to reduce the high-temperature peaks during the curing (Briones 1946). In this sense, the setting process of sand-cement mixes is slower than the portland cement mixes and it is highly affected by excess water, delaying the setting and hardening of the concrete.

The abandonment of the concrete produced with sand-cement was caused by the issues arising from its manufacturing and, in particular, the difficulty of obtaining a certain degree of fineness of the binder. Furthermore, the development of the cement industry around the same time contributed to that abandonment.

Precedents of Sand-Cement in Concrete Dams in the U.S.

Three dams were built in the United States during the second decade of the twentieth century: Arrowrock Dam, Lahontan Dam, and Elephant Butte Dam. Arrowrock Dam is an arch gravity structure that was completed in 1915 and achieved the world height record at the time (Hoffman 1954). Lahontan Dam is an earthen dam, whose power plant was built in 1911 with sand-cement concrete. Elephant Butte is a concrete gravity dam completed in 1916, but storage operation began in 1915.

Table 4 presents a summary of the main characteristics of each dam, including the height, the sand-cement proportions, and, if they apply, the degradation processes observed through the years. It should be pointed out that some of that information was not available for Lahontan Dam.

Table 4 shows that the sand-cement mixes contained over 50% of portland cement and the corresponding amount of pulverized granite in the case of Arrowrock Dam and sandstone in Elephant Butte Dam. In the 20 years following the construction of Arrowrock Dam, the downstream face and the coating of the channel for the spillway exhibited some signs of degradation. These parts of the dam were built with sand-cement mixes, which presented higher porosity and absorbed more water than the conventional concrete mixes employed in the rest of the dam. As a result of the freeze-thaw cycles, in 1927 several corrective measures were taken to avoid further degradation of such areas and to protect the surface of the concrete. Lahontan Dam also experienced degradation phenomena in the sand-cement concrete employed in itsconstruction. In fact, it was severely damaged by freeze-thaw cycles (Dolen 2002). Elephant Butte Dam did not experience such deterioration of the sand-cement concrete due to the drier conditions and milder climate in New Mexico.

Table 4. Concrete Dams with Sand-Cement in the U.S.

Dam	Location	Height (m)	Sand-cement	Degradation process
Arrowrock[a] (1911–1915)	Boise River, Idaho	110	55% portland cement 45% pulverized granite Fineness: 90% sieve no. 200	Degradation in downstream face due to porosity of sand-cement. Freeze-thaw cycles
Lahontan[b] (1911–1915)	Carson River, Nevada	49	—	Degradation in the spillways due to freeze-thaw cycles
Elephant Butte[b] (1911–1916)	Rio Grande river, New Mexico	81	52% portland cement 48% sandstone	No historical registers of degradation

[a]Data from Hoffman (1954).
[b]Data from the Dam Safety Office (2003).

Table 5. Proposal of Concrete Mixes for Camarasa Dam (Data from Martínez i Roig 1995)

Aggregate size	Mix proportions	
	Laboratory	Worksite
Aggregate 10–150 mm (%)	—	66.0
Aggregate 10–70 mm (%)	62.0	—
Aggregate 1–10 mm (%)	13.0	12.0
Sand 0.1–1 mm (%)	12.2	10.8
Sand 0–0.1 mm (%)	3.8	6.0
Portland cement (%)	9.0	5.2
Total	100	100

Camarasa Dam

General Characteristics

Camarasa Dam is a gravity dam located in the Noguera Parallersa River in northeast Spain. The dam presents a curved form in the ground plan with a radius of 300 m, a height from the foundations of 102 m, and a crest length of 461 m. The dam does not have any galleries inside; therefore, all the monitoring and data registration must be performed externally. The construction occurred in a relatively short time between November 1917 and September 1920. The volume of concrete employed for its construction is 218,000 m^3, using sand-cement as the binder in order to reduce costs (Martínez i Roig 1995).

The poor transportation infrastructure between the cement plant and the location of the dam made the use of portland cement as a binder a very expensive possibility. Hence, sand-cement was used mainly for economic reasons. The available information of that time indicates that the sand-cement mix was composed of 55% portland cement and 45% dolomitic limestone sand (in weight) extracted from the dolomitic rock where the dam is located. The definition of this proportion responded to the requirement of a specific weight of $2,450\ kg/m^3$. The maximum aggregate size was first set on 70 mm but was subsequently modified in the worksite to 150 mm in order to reduce the amount of cement as much as possible. Table 5 shows the sand-cement concrete mix in percentage of weight.

The specific weight obtained in the laboratory for the second mix proportion (*work-site mix* in Table 5) ranged between 2,440 and $2,660\ kg/m^3$. In view of the values of density, the mix was considered suitable for the purpose and the compressive strength reached fulfilled the established requirements (around 15 MPa). For these reasons, the second mix was accepted even though a minimum portland cement content of 11.5% from the total weight of the cement and the fine sand was requested. This was equivalent to $274\ kg/m^3$ of sand-cement, which was obtained by mixing 55% portland cement and 45% sand (from dolomitic limestone of the hillside of the dam) that were blended to a fineness for which the waste after passing the sieve no. 200 was not higher than 10% (Martínez i Roig 1995). Taking into account the previous requirements, three concrete mixes were used in the construction of Camarasa Dam with different purposes. The main properties of each mix are presented in Table 6.

Table 6 presents the two types of binders employed in the construction depending on its location in the dam and its purpose. The general criteria was to use portland cement in the areas subjected to higher stresses, whereas the use of different contents of sand-cement was considered suitable for the rest of the dam. The increase in the sand-cement content from 274 to $300\ kg/m^3$ responds to the low compressive strength obtained (1.2 MPa) in some of the tests performed during the quality control of the material during construction.

Current State of the Concrete in the Dam

A review of the historical documents and technical visits to the dam were essential to determine the current situation of the dam and to define the hypotheses regarding the origin of the degradation phenomena. On the one hand, the review of documents revealed that a problem that has historically affected the dam was been water infiltrations in the left abutment due to karst phenomena. Nevertheless, such infiltrations were mitigated significantly after the initial events by conducting extensive injections (Santasusana and Diz Bercedoniz 1926). On the other hand, previous studies on the dam assess the specific weight of the concrete in the body of the dam. For that reason, the managing body of the dam raises the issue of a possible loss in specific weight of the concrete.

Regarding the state of the concrete in the downstream face [Fig. 1(a)], a partial degradation is observed in localized areas. The damage, characterized by the loss of mass [Fig. 1(b)], is located between 20 and 70% of the height of the dam. The deterioration was more evident in the right abutment and in the bottom area of the left abutment. The most feasible cause for the degradation is the mild freeze-thaw cycles, since there is loss of binder (in some areas even 15 cm), but the aggregates remain undamaged. This hypothesis is reinforced by the presence of water and the higher likelihood of sun-shadow cycles in the severely damaged areas. However, the upstream face presents a good state of conservation [Fig. 1(c)].

No signs of deferred reactions (e.g., internal sulfate attack and alkali aggregate reaction) were detected in the body of the dam or in the auxiliary structures. Nonetheless, previous studies (García 2004) suggest an alkali carbonate reaction (ACR), which should be verified in the present study. ACRa represent a group of reactions between dolomitic aggregates and the constituents of the cement paste, specifically portlandite. The most extended method used to determine the presence of ACR in the concrete of Camarasa Dam is the method developed by Dickson (1965) and has been validated by several researchers (Friedman 1959; Warne 1962; Hutchinson 1974). The method involves the chemical attack of samples with HCl and selective staining with Alizarin red-S.

Table 6. Binders Employed in the Concrete of Camarasa Dam (Data from ENDESA 2011)

Location	Binder	Content (kg/m^3)	Theoretical specific weight (kg/m^3)	Purpose
Foundations and faces	Portland cement	250	2,450	Areas with high levels of stress in order to improve mechanical response
Body of the dam	Sand-cement	274	2,449	Inside and outside of the body of the dam
Bottom part of the downstream face		300	2,449	Improvement of mechanical properties due to unfavorable results during quality control
Crest		300	2,449	Crest of the dam

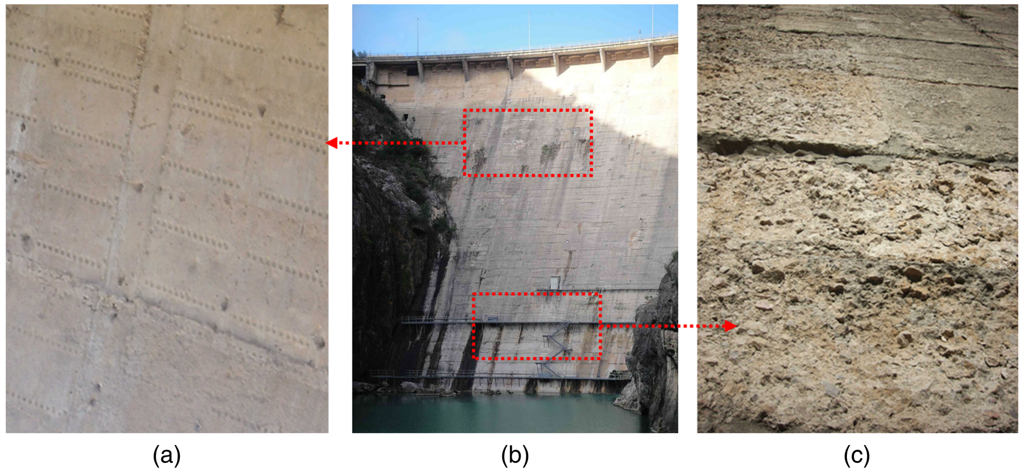

Fig. 1. Downstream face: (a) detail of higher areas; (b) general view; (c) detail of lower areas (reprinted from Conesa et al. 2015, with permission)

Taking into account the earlier discussion, the state of the structural elements is satisfactory considering the age of the concrete (almost 100 years) and without evidence of significant damage. However, given the partial degradation observed in the lower areas of the downstream face of the dam, an experimental program was performed to identify the origin of the phenomenon and the degree of the damage. This experimental program and the results obtained are described subsequently.

Experimental Program

The experimental program performed to assess the degradation phenomena in Camarasa Dam involved core drilling in the body of the dam. The definition of the location and number of cores to be drilled was conducted by considering the need to characterize the three concrete mixes employed in the dam and to assess the influence of the location and depth with respect to the downstream face. In order to maximize the profitability of the drilling, two types of cores were drilled. The first type (T1) corresponds to cores with a length of 3.0 m and was employed to assess the differences regarding the concrete mix. The second type (T2) has a depth into the body of the dam of 5.0 m and it is located near the left abutment, which exhibited leaking and, consequently, could accelerate the degradation process.

For T1, twin cores were drilled at three different heights, making a total of six cores of 3.0 m, and for T2, two cores were extracted at two levels, thus resulting in four cores of 5.0 m. In all cases, the diameter of the drill-bit was 75 mm and the resulting diameter of the cores was measured. The location of the drills in the downstream face and in the lateral view is presented in Fig. 2.

The main characteristics of the cores drilled from the body of the dam are summarized in Table 7. Notice that, theoretically, core S6 covers two different mixes since at a depth of 4.0 m with respect the downstream face, the proportion of sand-cement in the mix decreases from 300 to 274 kg/m^3.

Several tests were performed on the cores extracted from the dam regarding the physical and mechanical properties, in particular porosity tests [EN1936:2007 (AENOR 2007)], density tests [EN12390-7:2009 (CEN 2009b)], compression tests [EN12390-3:2009 (CEN 2009a)], and static modulus of elasticity tests

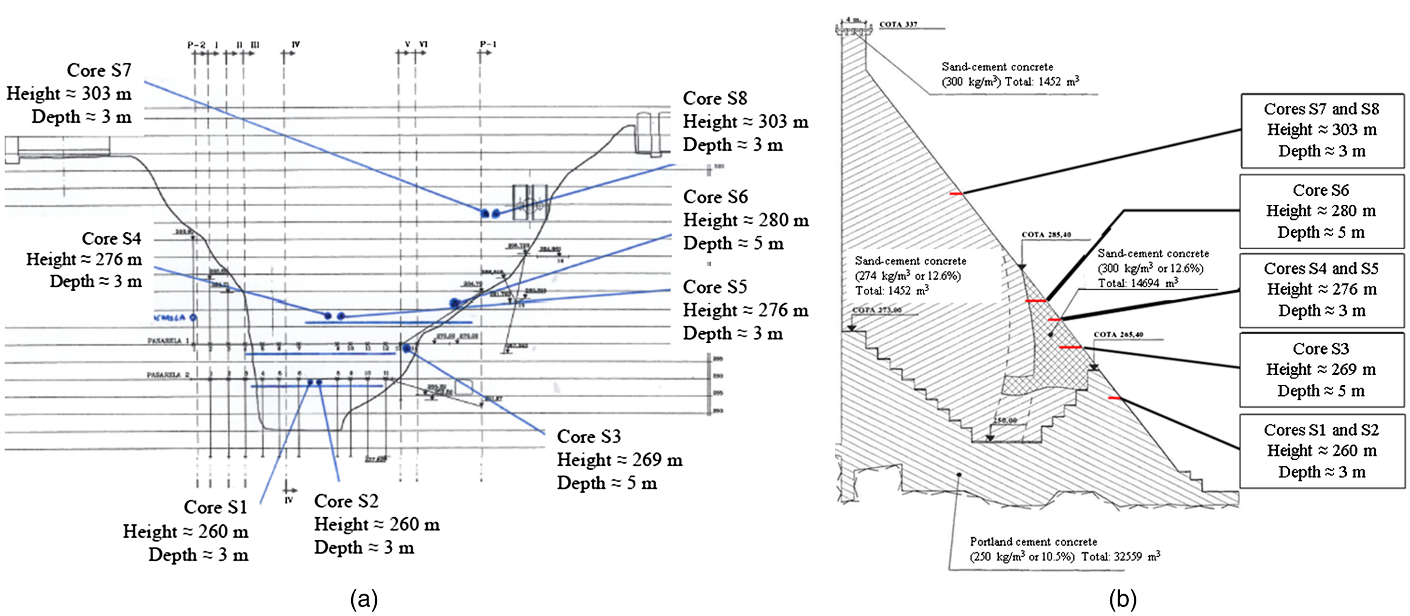

Fig. 2. Location of the cores in (a) downstream face; (b) lateral view (reprinted from ENDESA 2011, with permission)

Table 7. Characteristics of the Cores Drilled from the Body of the Dam

Type of core	Core	Height (m)	Length (m)	Binder	Binder content (kg/m^3)	Notation
T1	S1, S2	260	3	Portland cement	250	PC250
T2	S3	269	5	Sand-cement	300	SC300
T1	S4, S5	276	3	Sand-cement	300	SC300
T2	S6	280	5	Sand-cement	300/274	SC300/SC274
T1	S7, S8	303	3	Sand-cement	274	SC274

[EN12390-13:2013 (CEN 2013)]. In order to evaluate the presence of chemical reactions leading to degradations, several tests and procedures were also conducted. First, the samples were visually analyzed. The samples were then selectively stained with alizarin red-S and pH universal solution. Subsequently, X-ray diffraction analyses (XRD) were performed in samples extracted from the drilled cores to identify crystalline phases. Finally, scanning electronic microscopy (SEM) with energy dispersive X-ray analysis (EDAX) techniques were performed in selected samples to identify possible aggregate deleterious reactions.

To perform such tests, the cores were cut along their length into smaller samples and were stored in plastic bags under laboratory conditions (at 60% RH and 20°C) to avoid any physical or chemical alteration. The methodology followed to obtain representative samples of the concrete in the dam consists in (1) analyzing more than eight samples from the same core and (2) selecting samples from both edges of the cores and from the central zone. It must be remarked that samples in good condition and samples exhibiting physical damage were selected for the study.

In order to enable the interpretation of the results of density and porosity, an approach consisting in grouping the sample by zones and type of material was defined. Such an approach entails considering the summation of the values of mass and volume of all the samples. This allows increasing the amount of material in the calculations and, therefore, increases the representativeness of the results.

Physical and Mechanical Analysis

Visual Inspection

Visual inspection of the cores reveals that the cores extracted from the central area of the downstream face (cores S1, S2, S4, and S5) as well as the core S3 (extracted from the lower areas of the left abutment) exhibit a homogeneous aspect without significant signs of degradation. In some cases, a lack of bond in the aggregate-matrix interface was detected [Fig. 3(a)]. Furthermore, most of the cores exhibited aggregates with pores and cavities, some of which presented crystalline compounds.

The cores extracted from the left abutment of the dam at heights over 275 m (cores S6 and S8), showed more signs of degradation than others. Such degradation was caused by the lack of bond between the aggregate-matrix interface, cracking in the aggregates and the matrix, as well as cavities and green halos around certain aggregates.

Bulk Density, Apparent Density, and Porosity

Fig. 4 shows the bulk density (BD), apparent density (AD), and porosity (P) for all samples of each type of concrete according to their depth (with a depth lower or equal to 1.5 m and for a depth higher than 1.5 m) and on the core. In all cases, the confidence intervals for 90% of the standard deviation are presented. Note that the notations PC and SC correspond to portland cement and sand-cement, respectively.

In general, the apparent density in the surface ($X \leq 1.5$ m) is lower than in the inside of the dam, particularly in the case of sand-cement [Fig. 4(a)]. However, no significant differences are observed in the real density with the depth, even though the scatter is smaller [Fig. 4(b)]. This outcome suggests the existence of a degradation process in the external part of the dam, which reduces the apparent density of the concrete. Since the variation does not occur for the real density, the origin of such degradation is unlikely to be chemical but physical. The damage is more evident in the concrete with sand-cement, which is consistent with the state of the downstream face.

The results in Fig. 4(c) verify the existence of a higher porosity in the superficial layers, which leads to the reduction of the apparent density in such areas. This variation may be attributed to the boundary conditions during the construction process or to the material degradation. The first hypothesis is discarded since the depth selected was large enough with respect to the dimension of the aggregate in order to avoid the influence of the construction process. Consequently, the most feasible hypothesis is superficial degradation.

The results of density for each of the cores [Figs. 4(d and e)] indicate that no clear correlation exists between the location of

(a)

(b)

Fig. 3. (a) Lack of bond between aggregate-matrix in S5; (b) deterioration in matrix of S8 (reprinted from Conesa et al. 2015, with permission)

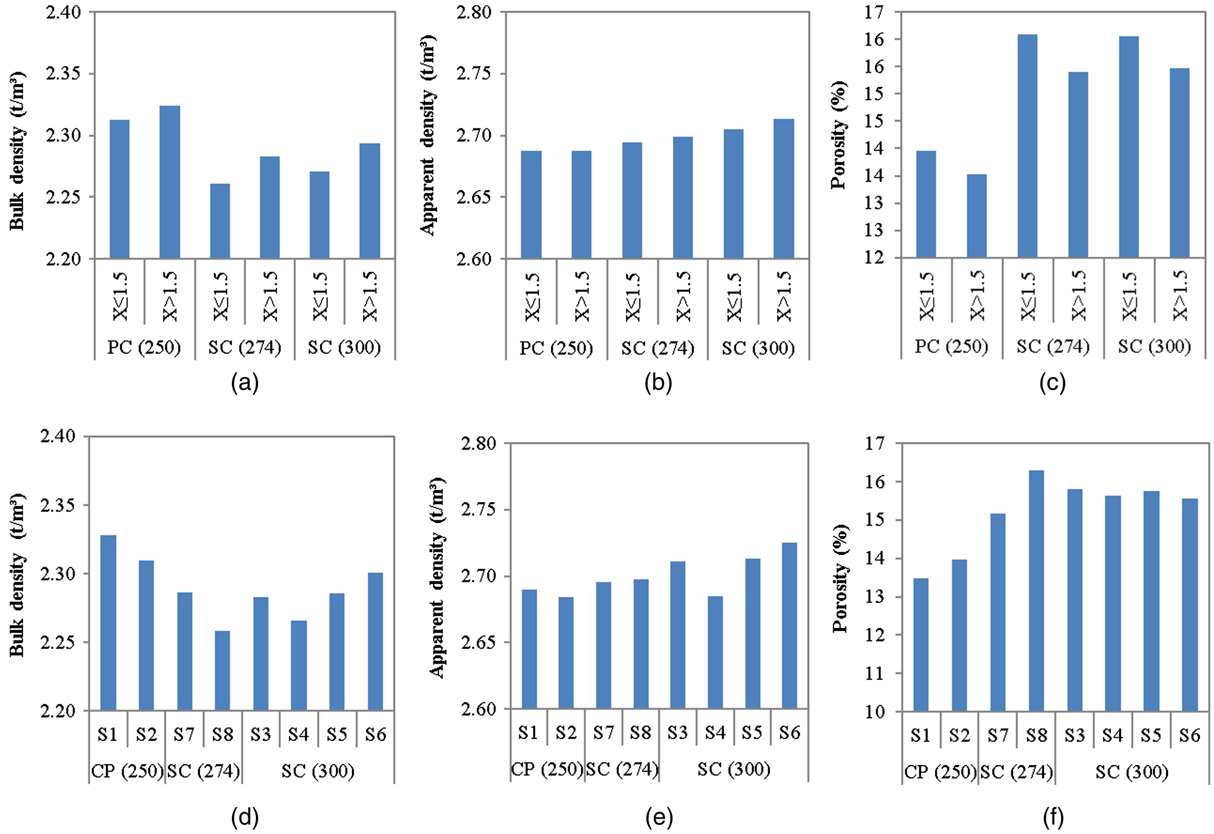

Fig. 4. Variation with the depth: (a) bulk density (BD); (b) apparent density (AD); (c) porosity (P); variation for each core: (d) bulk density (BD); (e) apparent density (AD); (f) porosity (P)

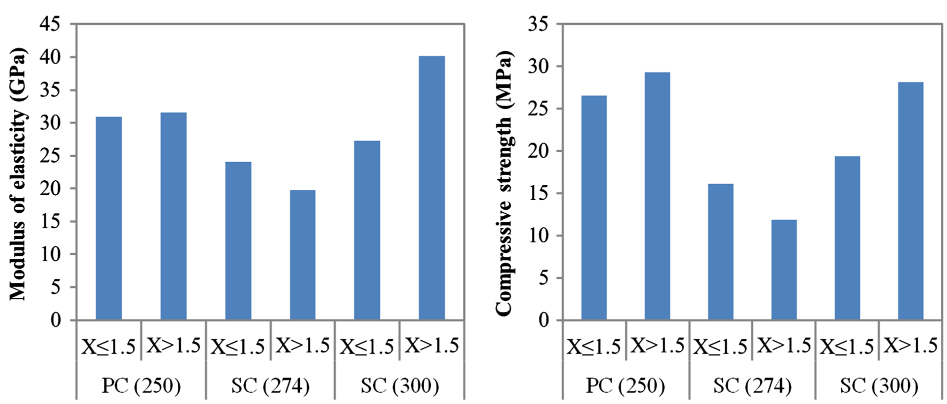

Fig. 5. Variation with the depth: (a) modulus of elasticity; (b) compressive strength

the core in the dam and the variation of density. For example, the cores located near the abutments (S3 and S6), in areas where infiltrations occurred, exhibit similar apparent densities to the cores that are located farther from the abutments (S4 and S5). The differences detected in such cases seem to be associated with the change of concrete type instead of the location in the downstream face.

The results of Fig. 4(f) corroborate the observations derived from the density analysis. Once more, the variations are not attributed to the location of the cores but rather to the composition of the concrete, i.e., the type of binder. Furthermore, smaller porosities were obtained for the concrete with portland cement [CP (250)] due to the higher content of clinker and the additional formation of hydrated phases.

Modulus of Elasticity and Compressive Strength

Fig. 5 presents the results of the modulus of elasticity and the compressive strength depending on the depth and the type of concrete. The values correspond to the average of the samples in the superficial areas and in the internal area. The dosages PC (250) and SC (300) exhibit an increase in the compressive strength in the internal layer, which is consistent with the results of density and porosity. Taking into account that the material should be

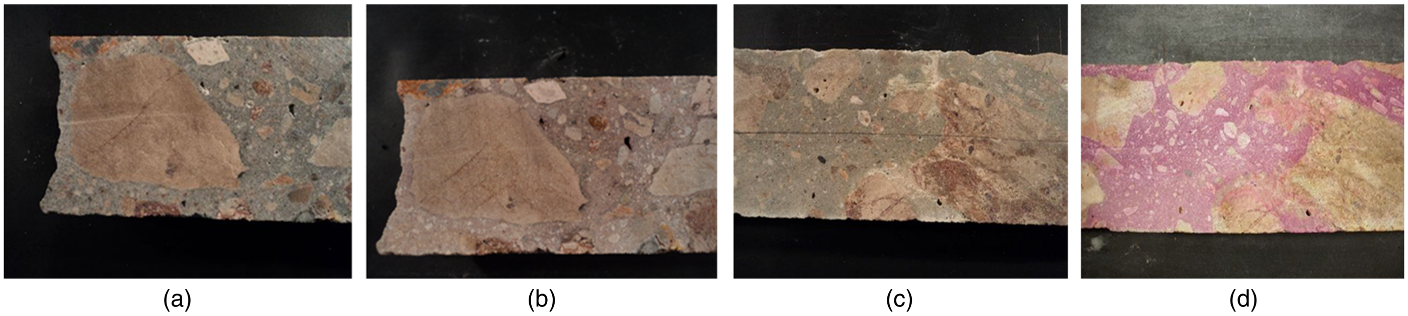

Fig. 6. Alizarin red-S staining in S1: (a) before staining; (b) after staining; universal pH staining in S3; (c) before staining; (d) after staining (reprinted from Conesa et al. 2015, with permission)

homogeneous in the studied zones, the variation observed may indicate a degradation process that is more evident for the sand-cement dosages than the portland cement dosages.

Possible Causes of Variation of the Properties

The results of the experimental program reveal a slight degradation of the properties of the concrete in the superficial layer in comparison with the internal zones. Even though the variations are small, it is necessary to find the possible causes for such phenomena. In this regard, the results of real density and apparent density reveal signs of a degradation process of physical origin. Since the surface of the downstream face is exposed to the weather conditions, two causes may be possible: superficial leaching of the concrete and exposure to freeze-thaw cycles.

The former occurs due to the permanent exposure over the years to infiltrations and to rainwater. This water has the capacity to dissolve and leach progressively the hydrated phases of the clinker, leading to the disaggregation of concrete. This phenomenon becomes more noticeable for concrete mixes with smaller amounts of clinker. This is consistent with the bigger variation of the density and the porosity depending on the depth in the cores with lower content of sand-cement.

A similar disaggregation occurs in the concrete exposed to freeze-thaw cycles. Given that the orientation of the downstream face of the dam is between south and southeast, the action of the solar radiations is stronger in winter than in summer, thus having less sun-shadow cycles in winter. During the summer, temperatures may range from a maximum of 35°C during the day to a minimum of 15°C at night, whereas in winter, these values decrease to 14 and −4°C, respectively. Such temperatures indicate that freeze-thaw cycles could occur during the winter in Camarasa Dam.

In order to evaluate whether this phenomenon could be present in the dam, temperature data registered from 2003 to 2012 were analyzed. The historical records of temperature consist of four discrete measurements taken at several times during the day every 24 h. Estimation of the number of freeze-thaw cycles was performed considering that the days that exhibited temperatures equal or lower to 2°C in the late evening would reach negative temperatures at night, thus starting a freeze-thaw cycle that would be completed the next day if positive temperatures were registered.

According to these criteria and based on the historical data collected, it is estimated that the dam is exposed annually to approximately 12 freeze-thaw cycles. Assuming that such frequency was maintained through the years, the dam was exposed to a total of 1,100 cycles from its construction to the present time, which is a number high enough to appreciate the consequences of the degradation.

Safety Issues

The degradation caused by the combination of a leaching process and freeze-thaw cycles could have significant consequences in terms of the safety of the dam. The loss of mass in a concrete dam could affect the stability of the structure given that the width capable of resisting the compressive stresses decreases. Therefore, the reference point for the sum of moment changes and the base width to compute the stiffness and the normal stresses is reduced.

Nevertheless, the extent and the consequences of both degradation phenomena in the case of Camarasa Dam are limited, affecting only a superficial layer of approximately 15 cm, and do not compromise the safety and functionality of the structure. For this reason, no tests were performed in this regard. No significant influence on the concrete properties is detected. Moreover, the affected area is rather small if it is proportionally compared to the body of the dam.

Chemical Analysis

Selective Staining

The samples selected to perform the selective staining presented a length over 10 cm and remained stored under laboratory conditions to avoid any damage. The samples selected for each type of staining were obtained from the edges of the core and also the central part, with five or more samples in all cases. After the staining with Alizarin red-S, most of the cores exhibited a pink coloring in the paste or no color at all [Figs. 6(a and b)]. Consequently, clear conclusions could not be drawn on the existence of a dedolomitization reaction. If that were the case, a purple staining of the cement paste would have proven the presence of brucite in the samples.

A similar situation occurs after analyzing the results of the pH universal staining. In general, a pink coloring was observed in the surface of most of the cores, which indicates a pH over 10 [Figs. 6(c and d)]. This outcome does not reveal a degradation of the material. The only areas where no coloring occurred were those that exhibited green halos.

Microstructural Analysis

X-Ray Diffraction Analyses

The samples extracted from the different cores were characterized by X-ray diffraction (XRD) analyses in order to assess the presence of crystalline compounds and identify them. The selected samples correspond to those that evidenced degradation of the cement paste, green halos around the aggregates, and crystallization zones. Fig. 7

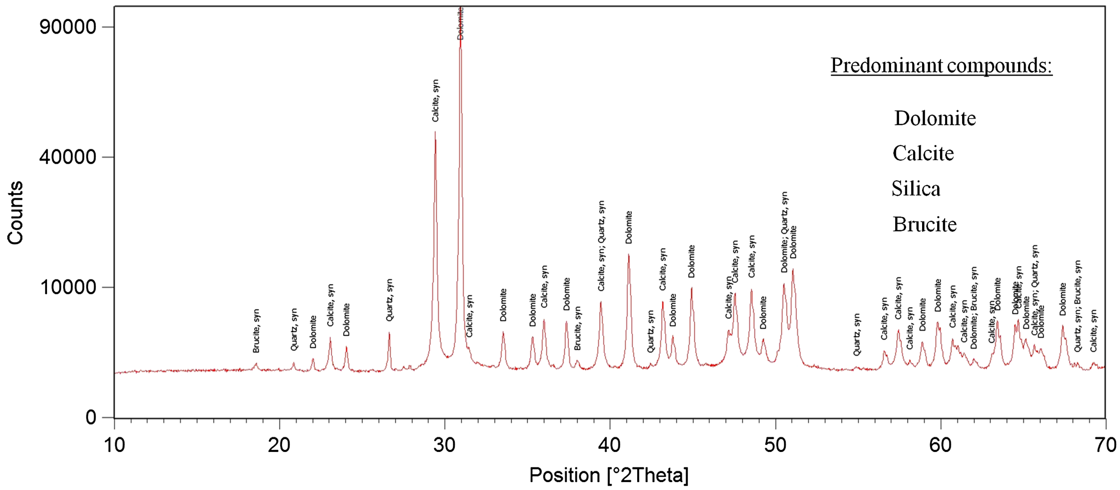

Fig. 7. XRD of the crystallization zone in core S3

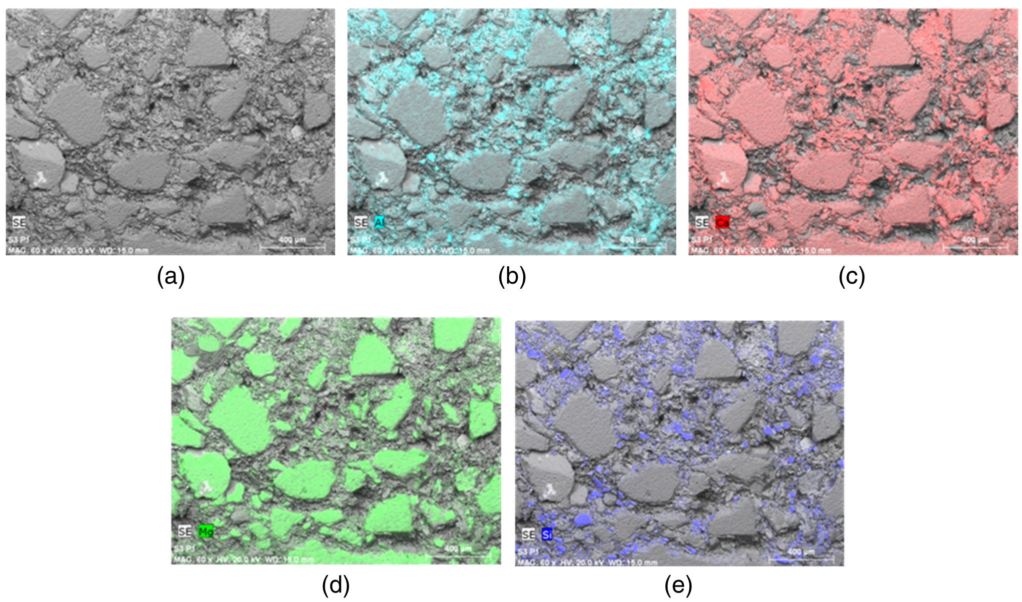

Fig. 8. Aggregate-matrix interface in a sample from core S3-zone 1: (a) SEM image; and maps by elements; (b) Al; (c) Ca; (d) Mg; (e) Si (reprinted from Conesa et al. 2015, with permission)

shows the diffractogram obtained in a sample from core S3 and the predominant compounds found include dolomite, calcite, quartz, and a minor presence of brucite.

The remaining samples analyzed with XRD present similar results. Only a small amount of brucite was found, which is one of the main products of the dedolomitization reaction, and in such cases it was found in internal samples and never in the aggregate-matrix interface area. This phenomenon indicates that the brucite was already present in the aggregate before the concrete was produced.

Scanning Electron Microscopy

For the analysis with scanning electron microscopy (SEM), samples from cores S1 and S3 were selected and the aggregate-matrix interface assessed to determine the existence of a dedolomitization reaction. From the SEM image and the EDX analysis, elemental composition maps were created. As an example, Fig. 8 shows the aggregate-matrix interface for core S3, which corresponds to a sample with sand-cement.

Even though Fig. 8 corresponds to a concrete with sand-cement, the content of Mg in the matrix is not high [Fig. 8(d)]. Instead, relatively large particles are found and a with low content in the matrix area. The aggregate-matrix interfaces do not reveal the existence of degradation phenomena. Likewise, the rest of the samples did not show evidence of degradation.

Conclusions

The main objective of the present study was to assess the state of 100-year-old concrete manufactured with sand-cement as a binder through the case of Camarasa Dam in Spain. The conclusions derived from the experimental program conducted are as follows:

1. The concrete degradation in the downstream face is manifested by a loss of mass due to a leaching process combined with

freeze-thaw cycles, which in some areas was favored by the presence of water infiltrations.

2. The concrete in the body of the dam exhibits satisfactory mechanical properties and good state of conservation. The possible loss of weight mentioned in previous studies does not affect the safety of the infrastructure since it is due to the degradation mentioned in the previous conclusion and represents less than 1% of the dam weight.
3. The experimental techniques and procedures employed to assess chemical reactions allow discarding any alkali carbonate reaction in the concrete of the dam. The brucite detected through XRD analyses is not located in the aggregate-matrix interface areas, which means that the brucite was present in the aggregate before the concrete was produced. Therefore, its origin is associated to natural karstification phenomena in the rock of the dam, which also explains the infiltration problems in the abutments.

Taking into account the aforementioned points, it may be concluded that there are no degradation phenomena that compromise the safety or functionality of the dam. The results obtained range between what could be expected for this type of concrete and the construction procedures available a century ago.

Acknowledgments

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